

High-Power Proton-Linacs

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Fermilab

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Outline

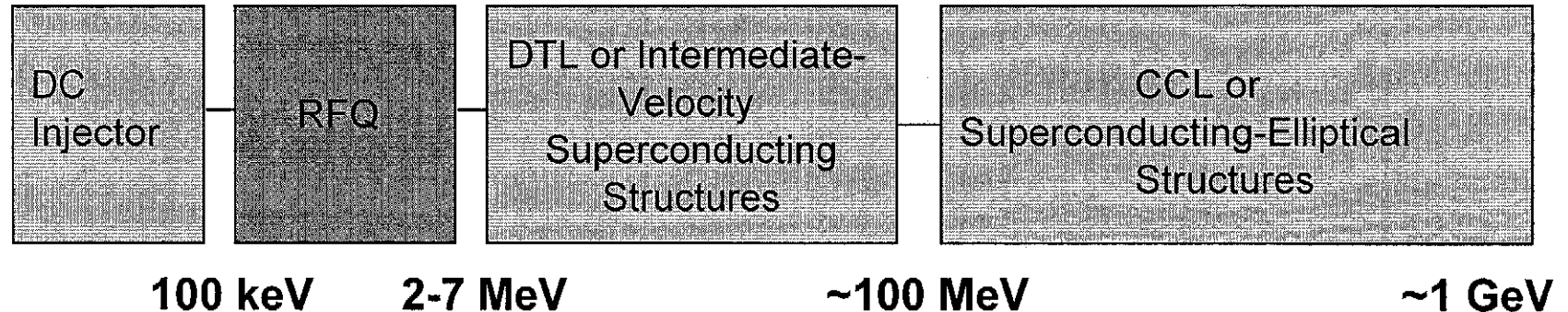
- **Introduction to high-power proton linacs / project survey.**
- **Superconducting versus normal-conducting linacs.**
- **Beam Dynamics Issues: LANL Beam-Halo experiment - some preliminary results.**

High-Power Linac Survey (H⁺, H⁻, D⁺)

- Projects in MW average power range.
- Applications include accelerator-driven subcritical reactors for nuclear-waste transmutation, neutrino factory, fusion-materials studies, injectors for spallation-neutron sources.
- LANSCE linac is the only high-power proton linac that has been built to this date. It has operated for almost 30 years.

Linac	Ion	Pulse length (msec)	Rep rate (Hz)	Duty factor	Bunch current (mA)	Average current (mA)	Final energy (GeV)	Ave beam power (MW)
LANSCE	H+/H-	0.625	100/20	6.25/1.25	16/9.1	1.0/0.1	0.8	0.8/0.08
SNS	H-	1.0	60	6.0%	52	2.0	1.0	2.0
CERN SPL	H-	2.8	50	14%	22	1.8	2.2	4.0
ESS	H+/H-	1.2	50	6.0%	107	3.85	1.33	5.1
FNAL 8-GeV	H+/H-/e-	1.0	10	1.0	25	0.25	8.0	2.0
KEK/JAERI	H-	0.5	50	2.5%	50	1.25	0.60	0.75
INFN-TRASCO	H+	∞	----	100%	30	30	>1.0	>30
IFMIF	D+	∞	----	100%	2X125	2X125	0.040	10.0

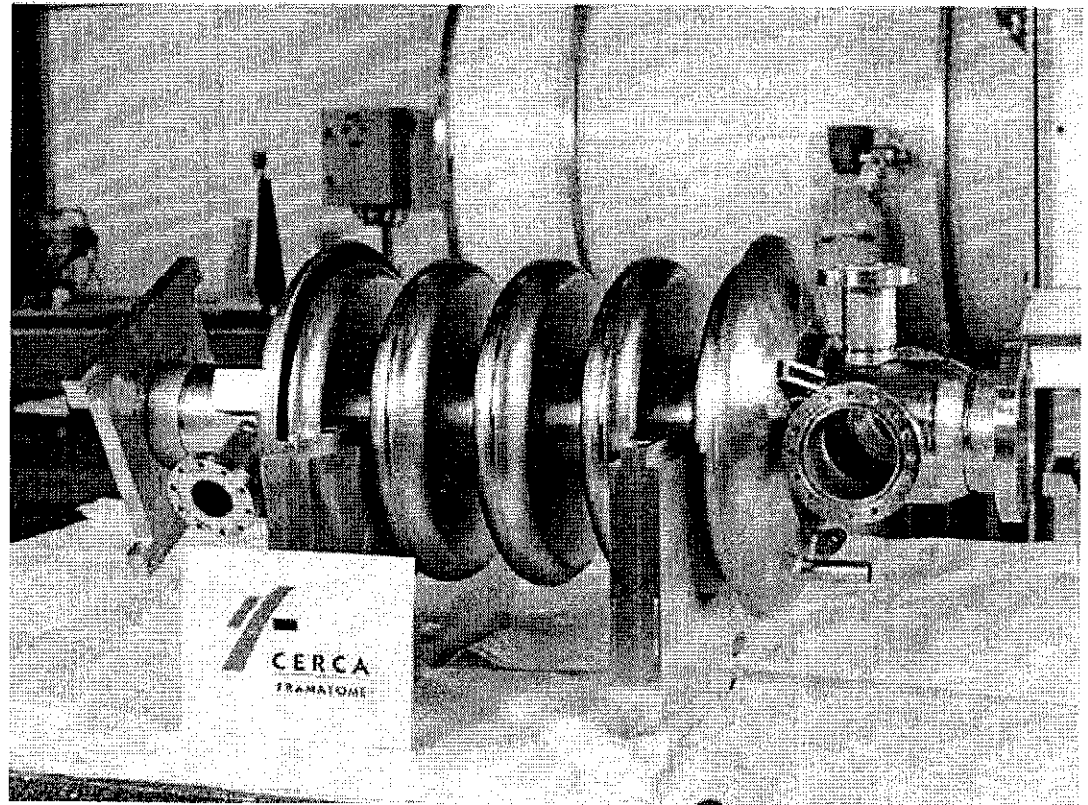
Modern Proton-Linac Layout



- Radiofrequency Quadrupole (RFQ) -normal conducting.
- Drift-Tube Linac (DTL) or intermediate-velocity superconducting structures (spoke-cavities, reentrant cavities, $\lambda/4$ cavities)
- Coupled-Cavity Linac (CCL) or high-velocity superconducting structures.

Elliptical cavities built for APT project and tested at LANL and TJNAF -- $\beta=0.64$

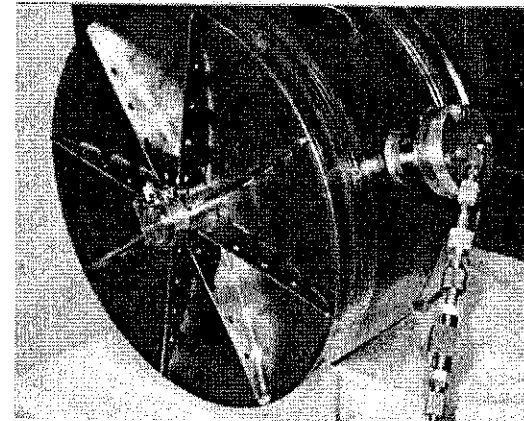
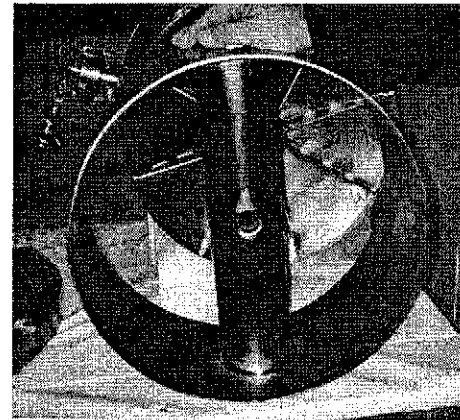
- 5-cell 700-MHz $\beta=0.64$ niobium elliptical structure built by CERCA for APT project.



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One of three spoke cavities built at ANL and tested at ANL and LANL - $\beta=0.3$

- 350 MHz, 2-gap, $\beta=0.3$
- The spoke structure is a half wave resonator.
- Additional spokes can be added to provide more cells per cavity.



SC versus NC in new high-power proton-linac projects.

- All 6 new high-power proton linac projects have SC sections. **SC has become the technology of choice.**
- Technology progress is making SC attractive.
 - Dramatic increase in **accelerating gradients**.
 - Higher power input **couplers**.
 - Pulsed-beam experience** at TESLA Test Facility and soon at SNS.
- However, cost studies for high-power proton linacs usually show no significant capital cost difference between SC and NC.

But advantages for SC extend beyond capital costs.

- Lower **operating costs**.
- **Larger bore radius** becomes affordable. Relaxes alignment, steering, and matching tolerances. Reduces beam loss/activation, eases commissioning, and improves availability.
- Independently-phased short cavities provide installed **redundancy** - can continue to operate even if an accelerating module fails.
- Worldwide **industrial capability** exists for fabrication of cavities and cryomodules. There are more commercial firms that build SC cavities than NC.
- The performance of the SC cavities is **still improving**.

LANL Beam Halo Experiment at Low Energy Demonstration Accelerator (LEDA)

Beam-halo experiment presentations - Wednesday afternoon - WG II - Linear Accelerators:

**Pat Colestock et al., Measurement of Beam Halo Generation
in an Intense Proton Beam**

**J.D.Gilpatrick et al., Wide Dynamic Range Beam Profile
Instrumentation for Beam-Halo Measurement**

Halo Experiment Scientific Team

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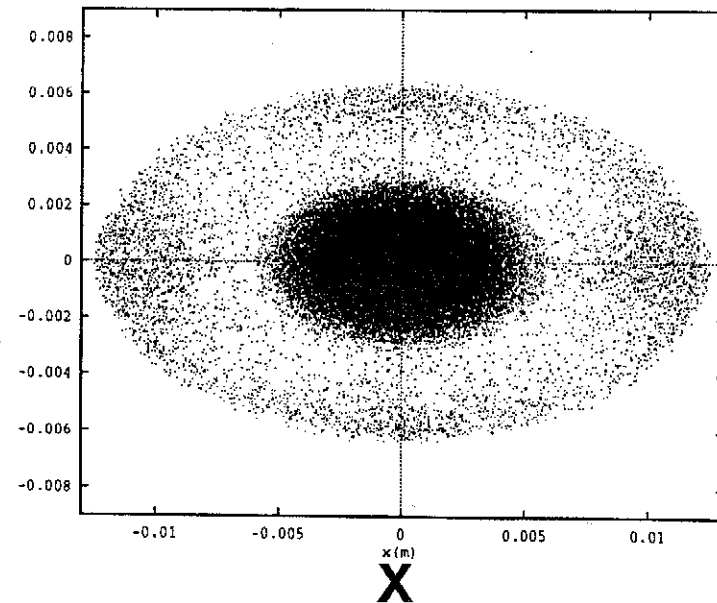
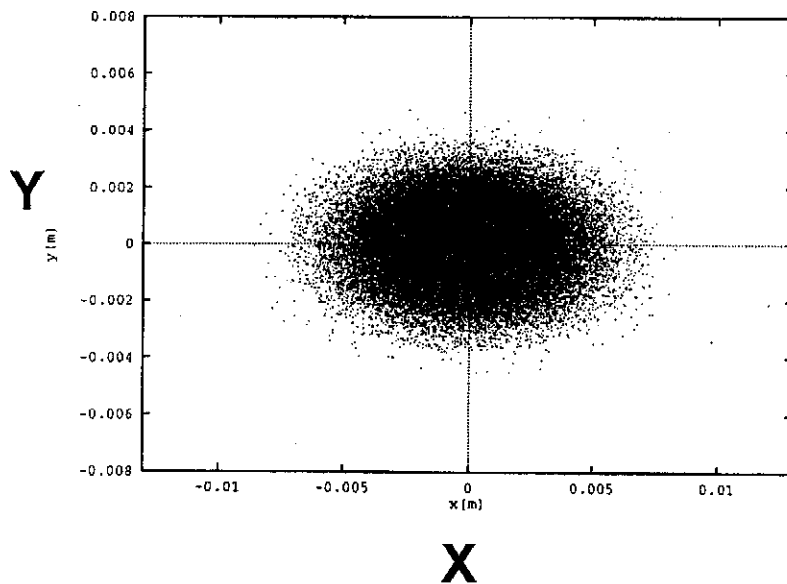
T.P.Wangler

Progress in understanding beam halo during past decade

- **Theoretical framework for halo in linacs was developed from:**
 - **computer simulations.**
 - **particle-core model with 2:1 resonance of individual particles with coherent mismatch oscillations.**
- **But no experiments had been done with proton beams until the halo experiment on LEDA was carried out last year.**
- **Motivation for halo experiment was to:**
 - **understand the physics.**
 - **test the predictive capability of simulation codes.**

Computer simulations showed halo is formed in mismatched beams.

Rms mismatched beam (on right) develops larger amplitudes than rms matched beam (on left).



Particle-Core model gives physical picture of mismatch halo growth.

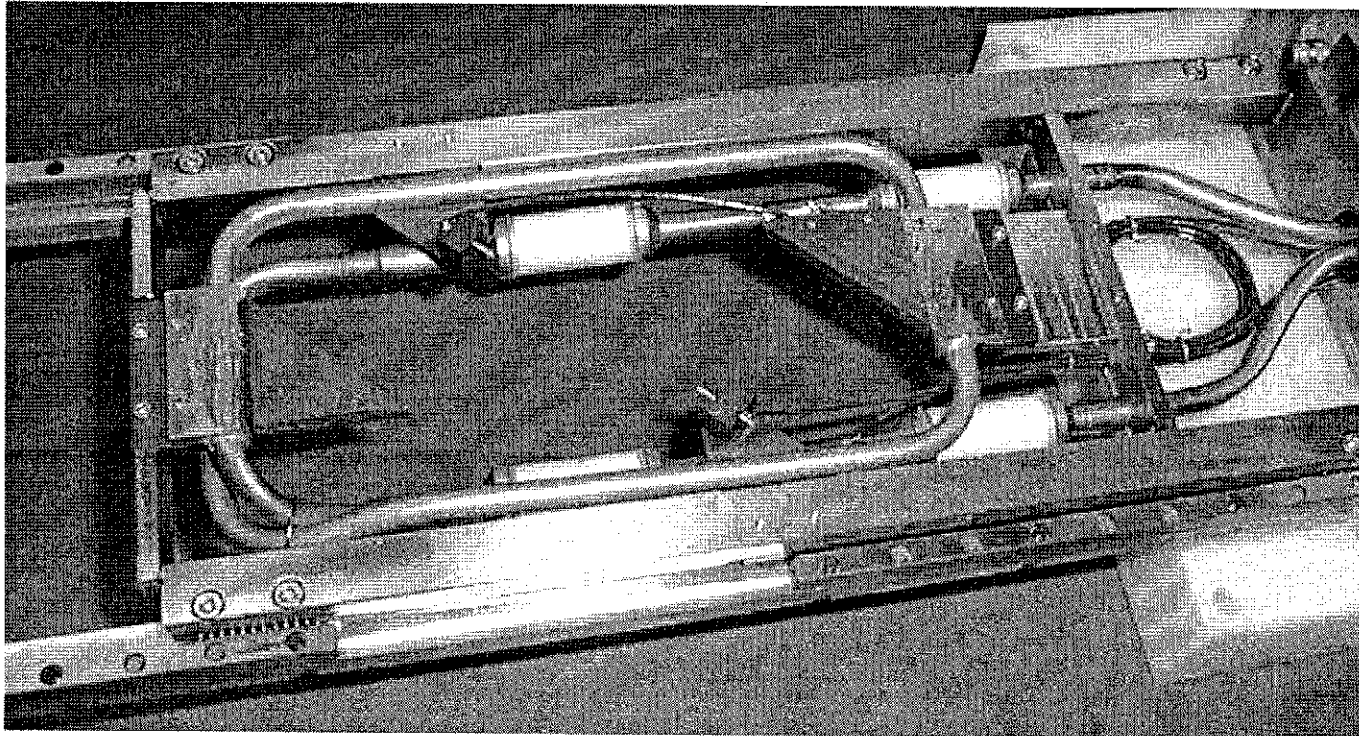
- Mismatch excites collective beam modes (breathing and quadrupole).
- Space-charge of oscillating core resonates with individual particles when $f_{\text{particle}} = f_{\text{mode}}/2$. A 2:1 parametric resonance (R. Gluckstern).
- Model predicts maximum particle amplitudes - up to 6 rms in our experiment.
- But details such as halo and rms-emittance growth rates require computer simulation or experiment.

Beam-halo experiment was designed to study halo growth by measuring beam profiles of mismatched beams.

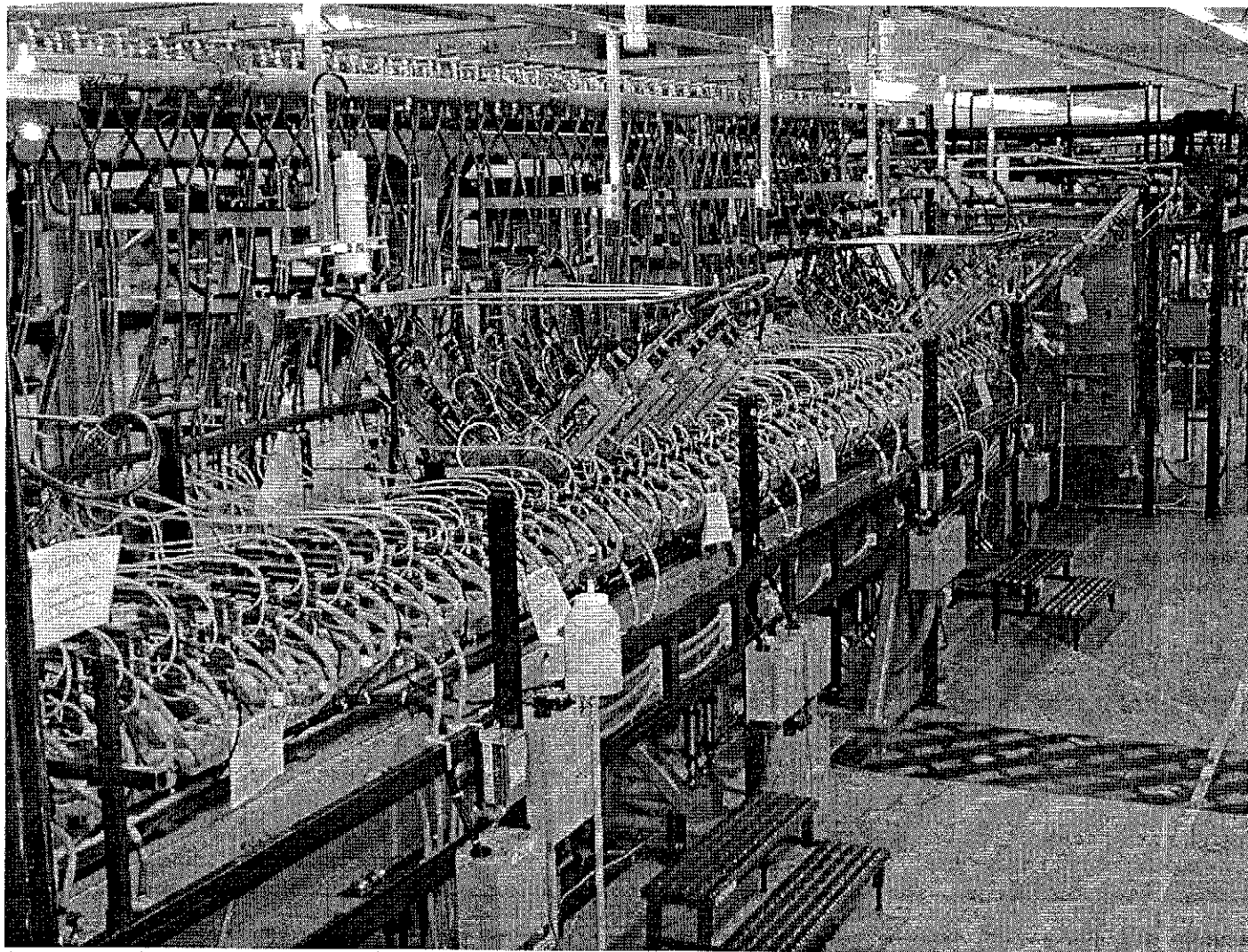
- **Pulsed beam from 6.7-MeV LEDA RFQ in 52 quadrupole transport line. First four quadrupoles create mismatches.**
- **10 envelope-mode oscillations, enough to see initial stages of emittance growth and halo-formation.**
- **Beam debunches longitudinally reducing transverse space-charge forces. We still expected measurable effects.**
- **Vary mismatch (first 4 quads) and vary current. Measure beam profiles to obtain: 1) rms emittances, 2) maximum detectable amplitudes, and 3) halo parameter based on 4th moments.**

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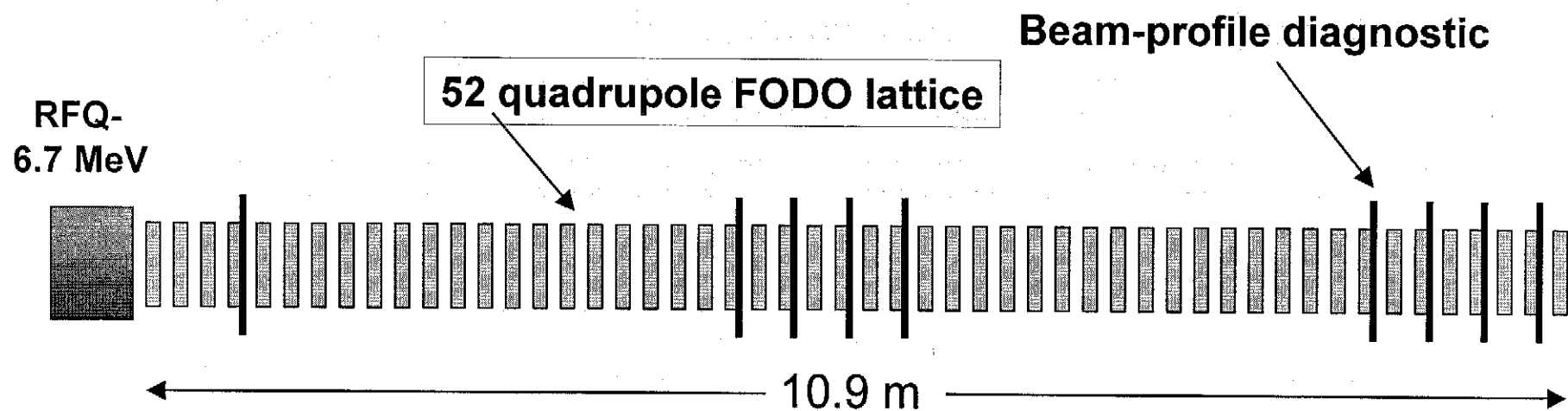
Wire and halo scraper assembly of the beam-profile diagnostic (J.D.Gilpatrick, et al.)



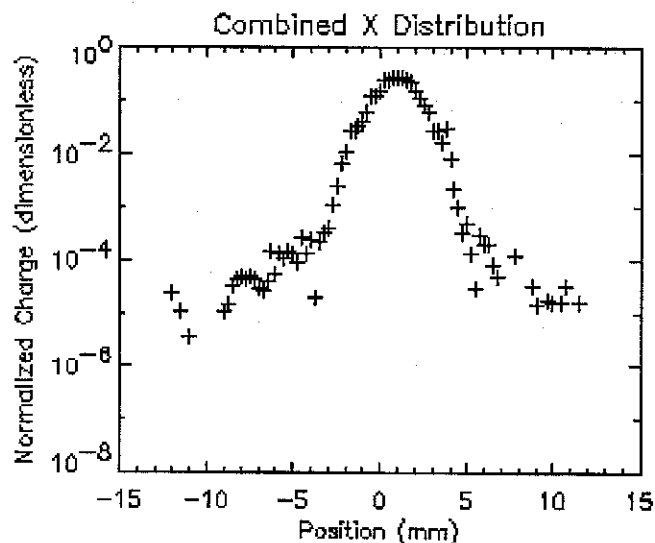
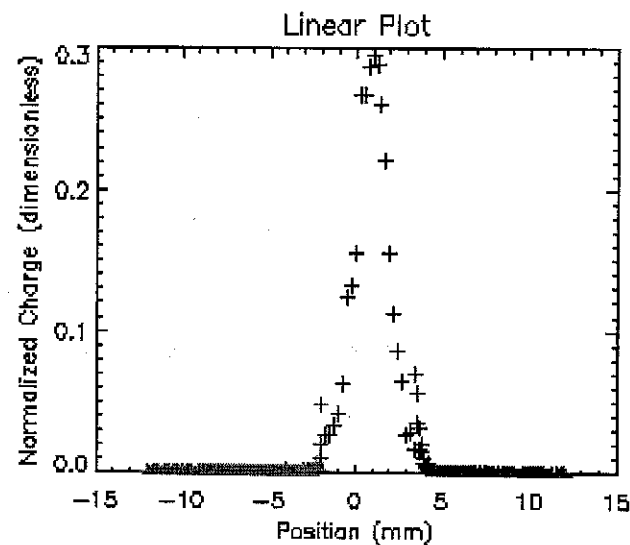
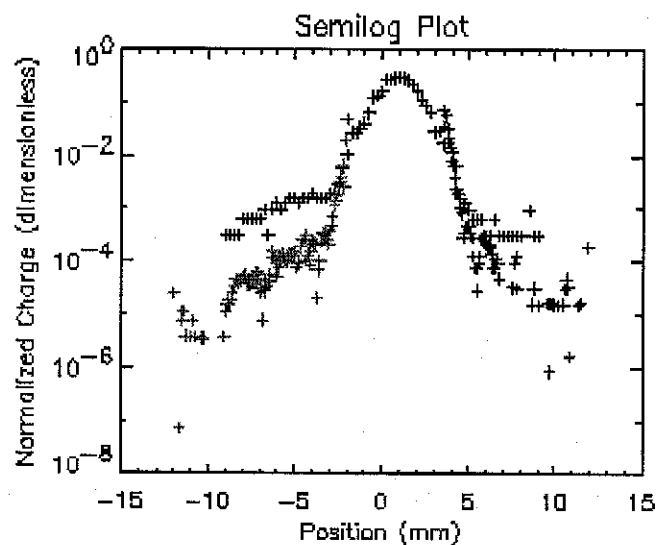
52 quad -11m beam channel after LEDA RFQ



Beam-halo experiment with layout of beam-profile diagnostics.



Matched beam - 75 mA - scanner 51x



Calculated Moments of the Combined Distribution

File: /u2/optdvl/wsha_data/2001_May_2_22_31_z51.rwa

Mean: 0.93145387 mm

Std Dev: 1.1019562 mm

Skew: -0.22773781

Kurtosis - 2: 1.3098605

Where Signal to Noise > 2.5

Negative halo scraper -8.32410 mm

Positive halo scraper 5.82570 mm

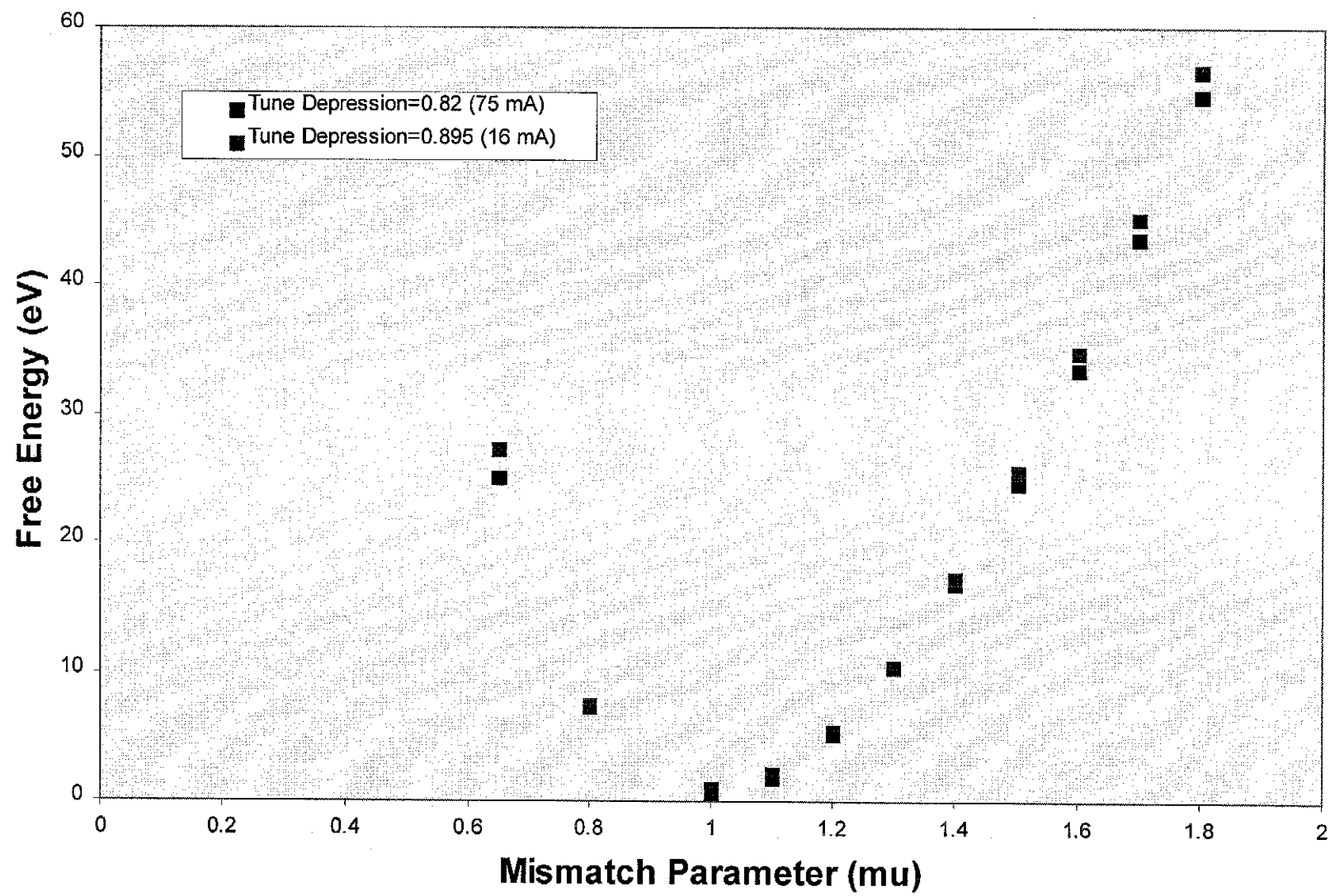
Initial stages of halo growth can be studied by analyzing rms emittance growth.

- We observe large amplitudes ~ 9 rms present in matched beam. These already exceed maximum amplitudes expected from beam mismatch.
- Simplest explanation: These large amplitudes are already present in the input beam.
- But we expect halo growth from beam mismatch to produce rms emittance growth.
- **We can measure rms emittance growth which can be compared with emittance growth upper limits based on free energy.**

Free Energy and Transverse RMS Emittance Growth in Mismatched Beams*

- Total transverse energy per particle: $E = KE + PE + \text{Self Energy}$.
- Free Energy: $F = E(\text{initial mismatched beam}) - E(\text{equivalent initial matched beam}) > 0$.
- As mismatched beam relaxes to a final matched beam, the emittance grows as free energy is converted to kinetic energy.
- **The maximum emittance growth corresponds to complete transfer of free energy.**
- Analytic formula for maximum emittance growth depends on initial mismatch and tune depression. See M.Reiser, "Theory and Design of Charged Particle Beams".

Free Energy



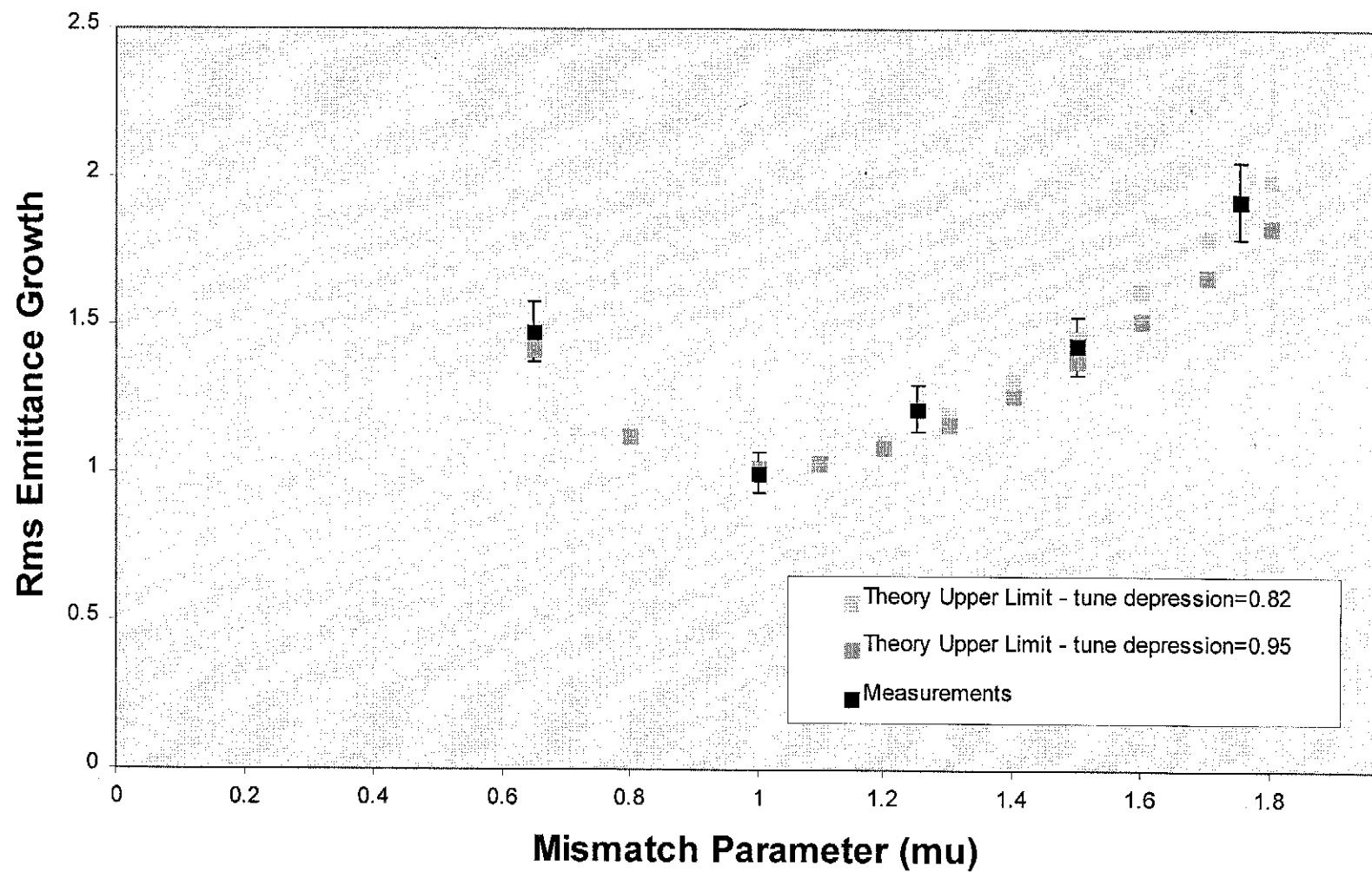
We calculate rms emittances from the beam-profiles using each set of 4 beam-profile diagnostics.

- Do least-squares fit of calculated to measured rms sizes at four scanners for each of the two scanner clusters. Emittances calculated at #20 and #45.
- Adjust 4 transverse Courant-Snyder ellipse parameters and 2 transverse emittances to fit 8 rms sizes in x and y.
- Minimize figure of merit:
$$\Sigma (X_{\text{rms,meas}} - X_{\text{rms,calc}})^2 + \Sigma (Y_{\text{rms,meas}} - Y_{\text{rms,calc}})^2$$

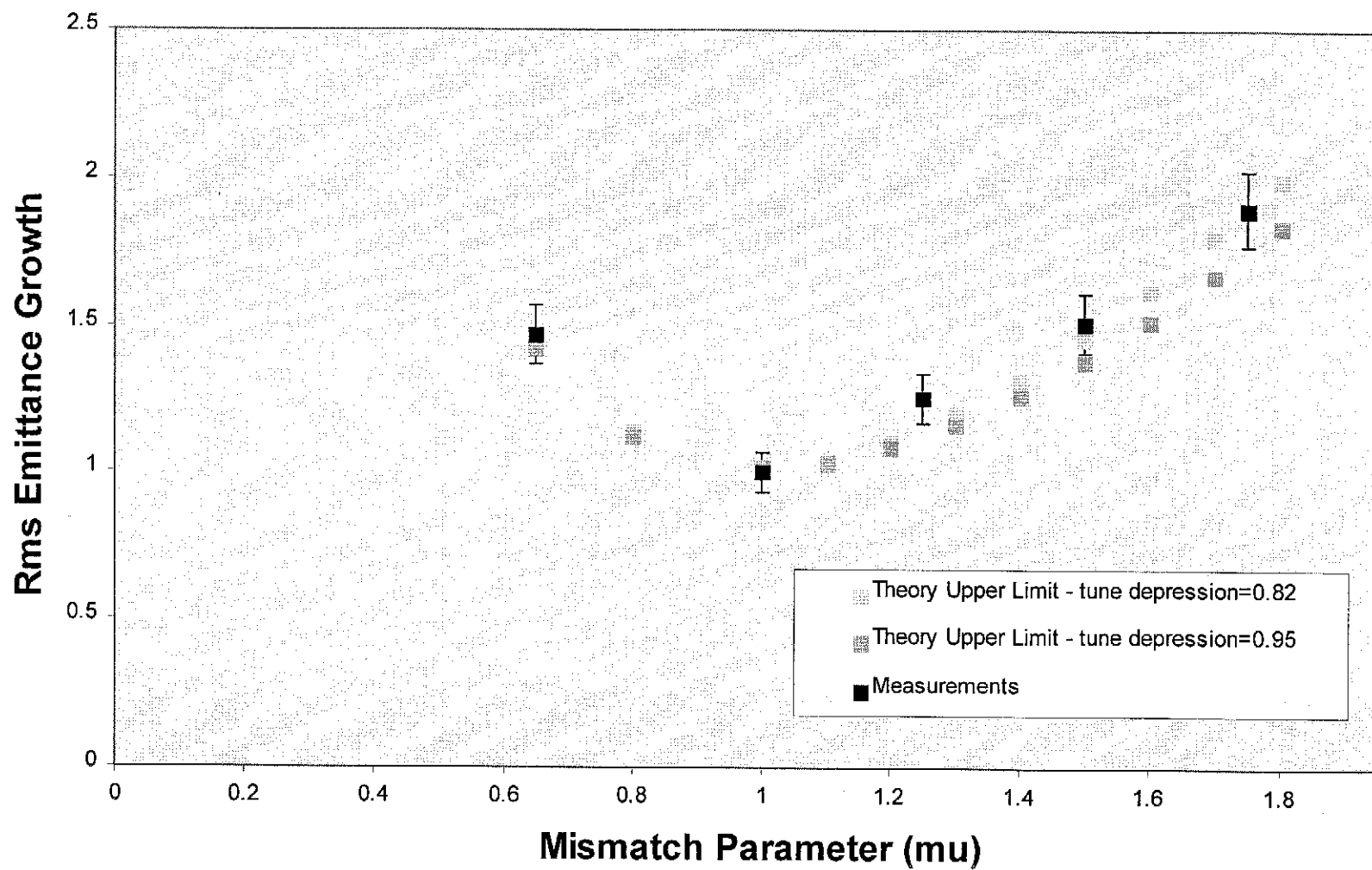
Tunes (phase advance per focusing period) and
tune depressions.

Beam Current (mA)	$\sigma_0(\text{deg})$	σ/σ_0
16	$\sim 73^\circ$	0.89- \rightarrow 0.99
75	$\sim 73^\circ$	0.82- \rightarrow 0.95
100	$\sim 73^\circ$	0.75- \rightarrow 0.95

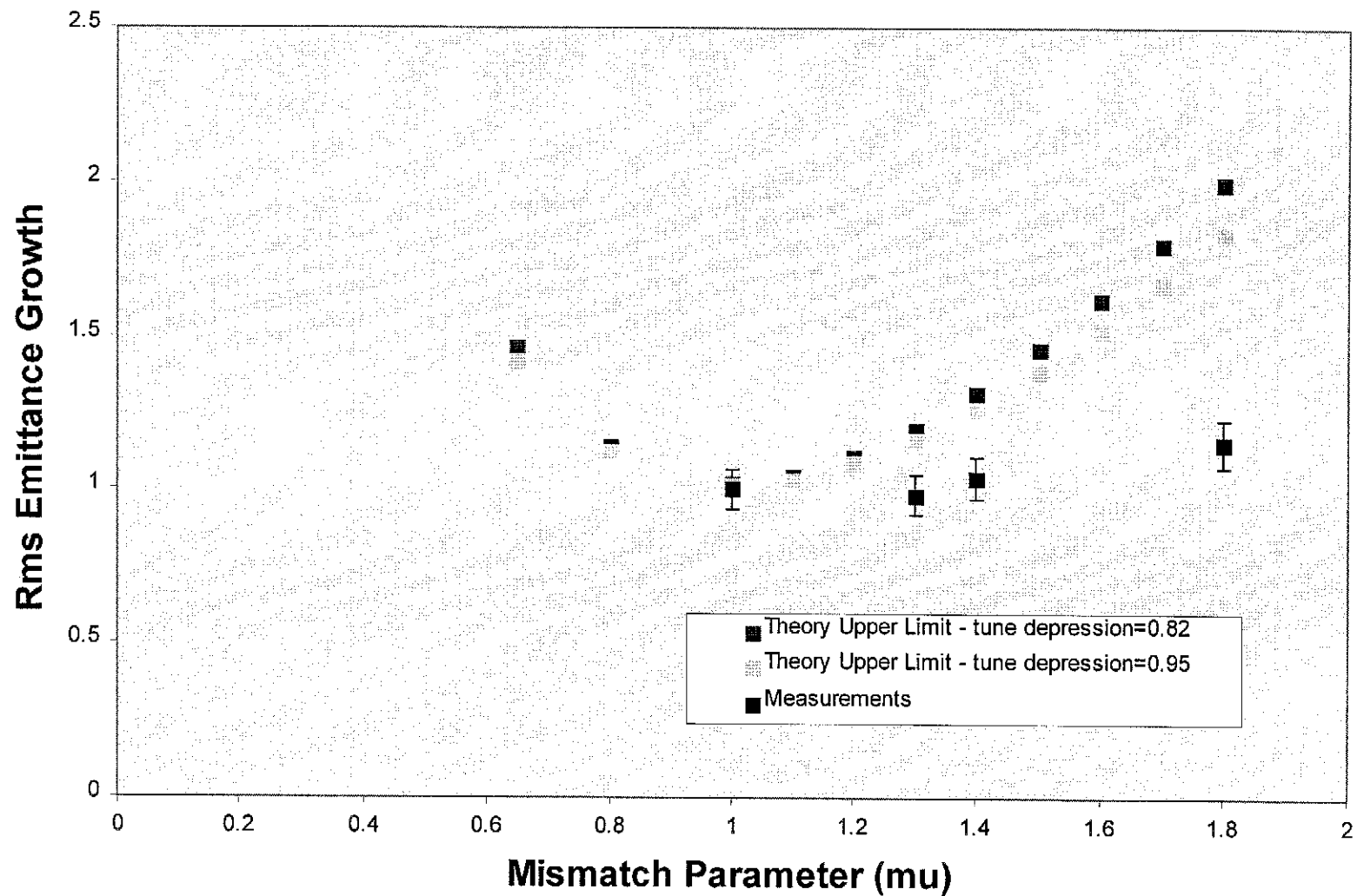
RMS EMITTANCE GROWTH AT SCANNER #20 - 75 mA - BREATHING MODE



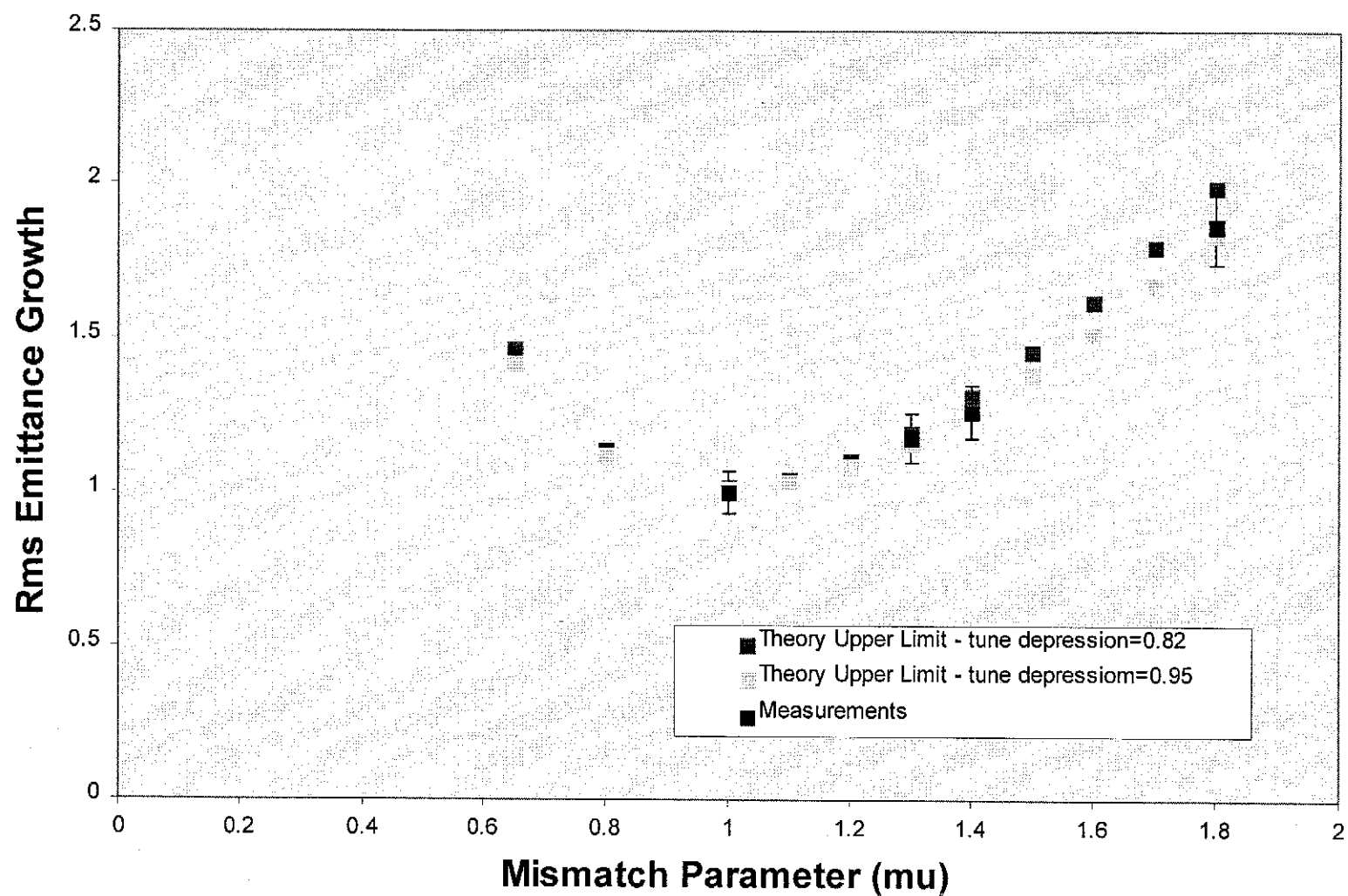
RMS EMITTANCE GROWTH AT SCANNER #45 - 75 mA - BREATHING MODE



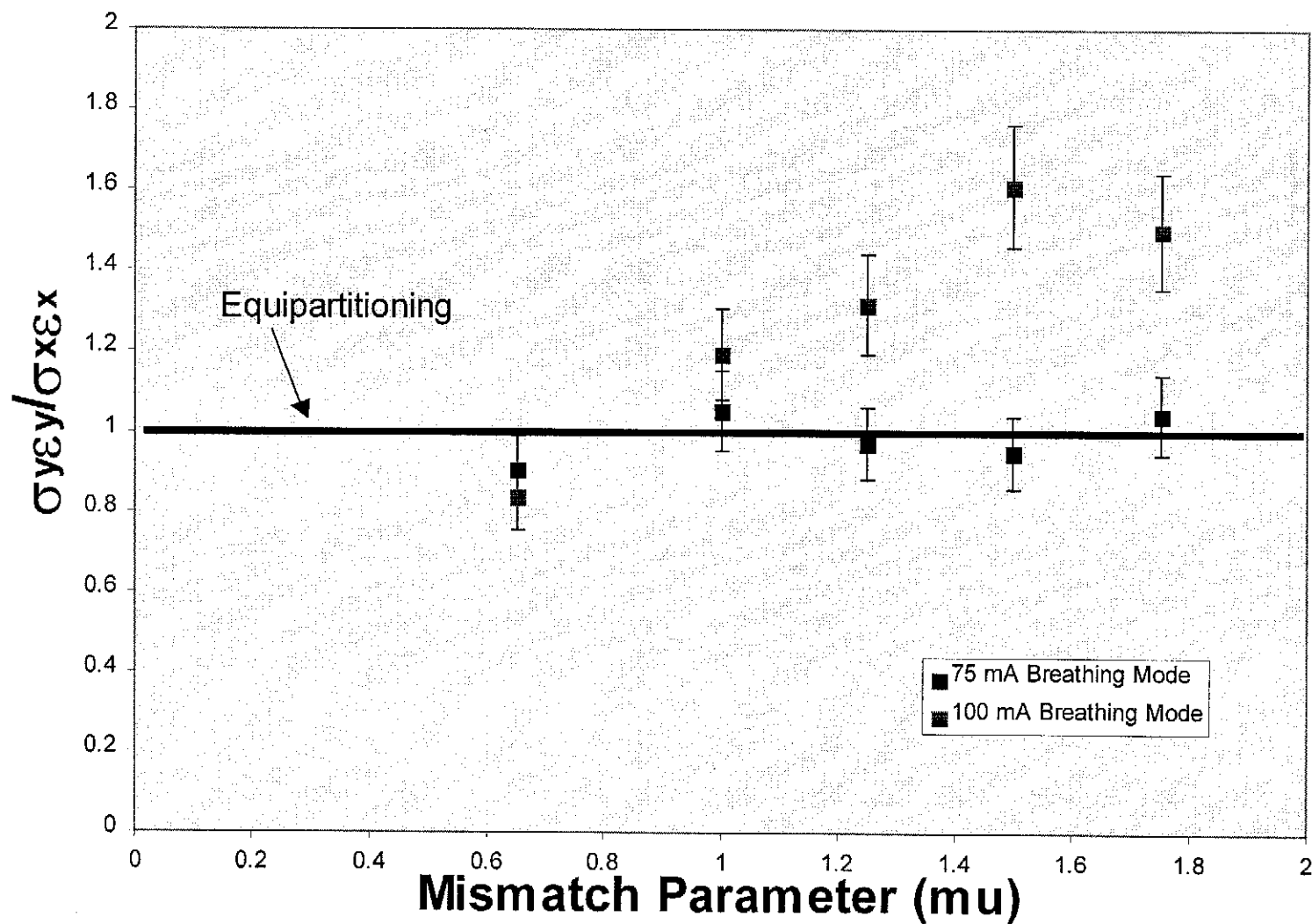
RMS EMITTANCE GROWTH AT SCANNER #20 - 75 mA - QUADRUPOLE MODE



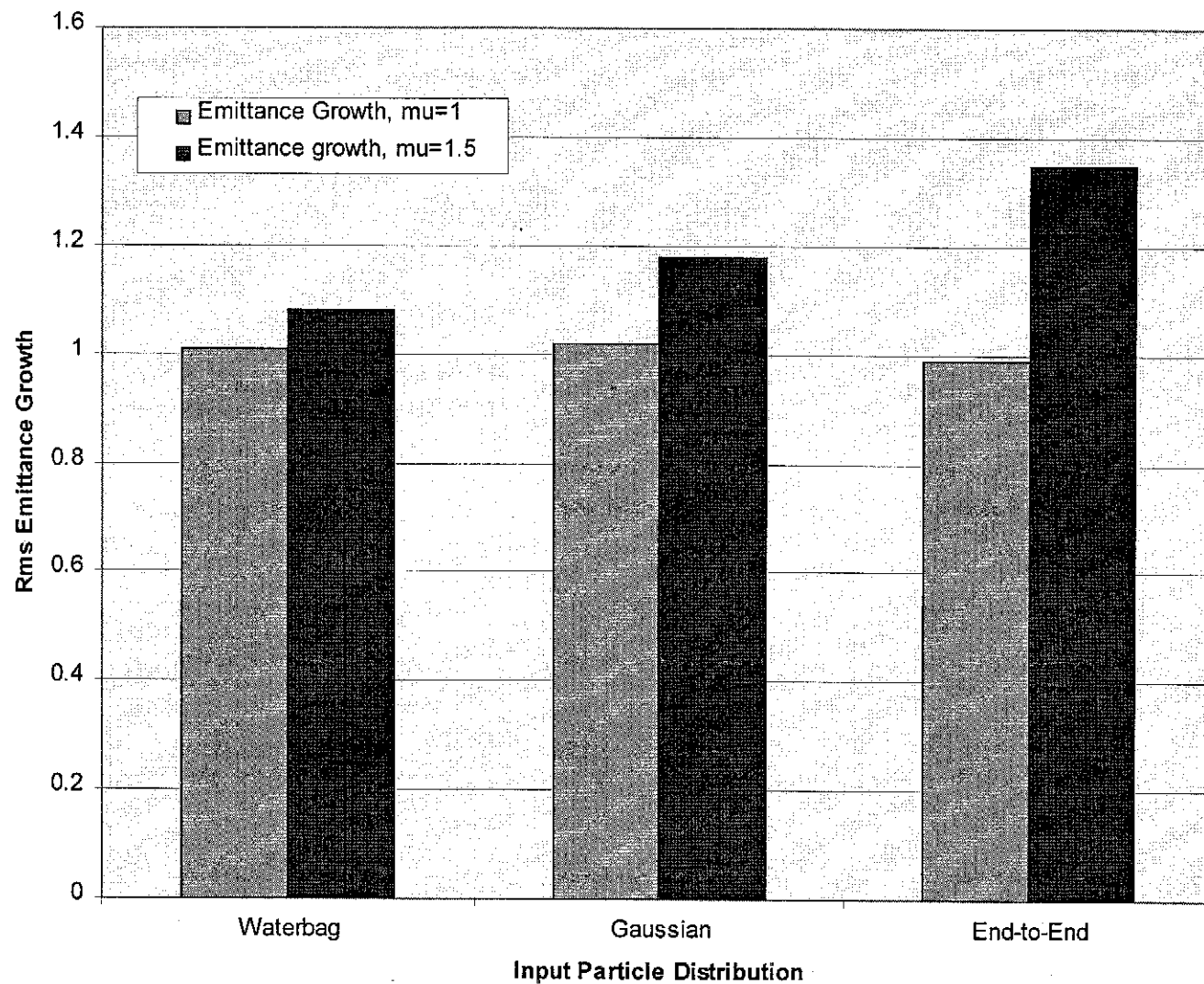
RMS EMITTANCE GROWTH AT SCANNER #45 -75 mA - QUADRUPOLE MODE



Temperature Ratio for X and Y Planes: $\sigma_{y\epsilon y}/\sigma_{x\epsilon x}$



**RMS EMITTANCE GROWTH FROM SIMULATIONS FOR DIFFERENT INPUT DISTRIBUTIONS -
75 mA - Breathing Mode**



Summary of Halo Experiment (1)

- The new beam-profile diagnostic has opened a **new regime for observing halo** to densities as low as 10^{-5} of core density.
- The large amplitudes observed in the matched input beam suggest for some projects a need for collimation at low energies.
- Our results are consistent with **complete free-energy transfer** to emittances in only 10 oscillation periods. The mismatch emittance-growth mechanism is very strong.